

Experimental violation of Svetlichny's inequality

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It is well known that quantum mechanics is incompatible with local realistic theories. Svetlichny showed, through the development of a Bell-like inequality, that quantum mechanics is also incompatible with a restricted class of *nonlocal* realistic theories for three particles where any two-body nonlocal correlations are allowed [31]. In the present work, we experimentally generate three-photon GHZ states to test Svetlichny's inequality. Our states are fully characterized by quantum state tomography using an overcomplete set of measurements and have a fidelity of $(84 \pm 1)\%$ with the target state. We measure a convincing, 3.6σ , violation of Svetlichny's inequality and rule out this class of restricted nonlocal realistic models.

INTRODUCTION

Quantum mechanics cannot be described by local hidden-variable (LHV) theories. This is the conclusion of Bell's seminal work, in which he derived a strict limit to the strength of correlations achievable by all LHV models that is violated by quantum predictions [1]. Bell's original inequality did not allow for imperfections and thus it was not accessible to experimental tests. Clauser, Horne, Shimony and Holt (CHSH) addressed this issue and developed the CHSH inequality [2], which allowed for tests in actual experiments. Since then a growing number of experiments have been reported (for examples, see [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]), and the overwhelming experimental evidence from these tests is in favour of quantum mechanics, ruling out LHV theories. It should be noted that, while no *loophole-free* Bell test has been performed, the most significant potential loopholes, relating to detection efficiency and space-like separation of the choices of measurements settings, have both separately been closed [6, 12, 13].

Both Bell's inequality and the CHSH inequality were formulated for testing the correlations between just two particles. For more than two particles, Greenberger, Horne and Zeilinger (GHZ) showed [19] that a contradiction between LHV theories and quantum mechanics can be seen directly in perfect correlations, as opposed to statistically in imperfect ones. Soon thereafter Bell-type inequalities for more than two particles were developed [20, 21, 22, 23, 24, 25, 26, 27, 28]. Quantum predictions can violate such inequalities by an amount increasing exponentially with the particle number [20, 21, 23, 24, 25, 27].

All of the aforementioned inequalities are based on the assumption that local realism applies to each individual particle. Two-particle inequalities have been developed which are in conflict with quantum mechanics although they allow restricted, but physically motivated, nonlocal correlations [29]. These inequalities have recently been violated experimentally [30].

Svetlichny showed that even if one allows unrestricted nonlocal correlations between any two of the constituent particles in a three-particle setting one can still find inequalities violated by quantum mechanical predictions [31]. The correlations allowed by Svetlichny's model are strong enough to maximally violate three-partite inequalities, such as Mermin's [32], which assume local realism for all particles involved. A violation of such inequalities

therefore can only rule out LHV theories, while a violation of Svetlichny's inequality directly rules out a whole class of nonlocal hidden-variable theories [32, 33, 34, 35, 36]. Svetlichny's work has since been generalized to the case of N particles [37, 38, 39].

Experimental tests have been performed confirming the violation of the Mermin inequality [40], the Mermin-Ardehali-Belinskii-Klyshko (MABK) inequality [41], and the cluster state inequality developed by Scarani et. al. [42]. For an even number of particles only, a sufficiently large violation of the MABK inequality also rules out partially non-local hidden-variable models [38]. The violation of the MABK inequality in [41] thus confirmed genuine four-particle entanglement and non-locality. The original Svetlichny inequality, however, remains untested.

Here, we begin with a brief theoretical description of Svetlichny's inequality. We then experimentally produce high-fidelity three-photon GHZ states and characterize them via quantum state tomography [43]. Using these states, modulo standard loopholes [6, 12, 13], we experimentally demonstrate a convincing violation of Svetlichny's inequality.

THEORY

The two assumptions resulting in Bell-type inequalities are locality and realism as they were introduced by Einstein, Podolsky and Rosen [44]. We first review a straightforward method to derive the CHSH inequality from these two assumptions following an argument described by Peres [45]. Pairs of particles are distributed to two distant parties, A and B. Party A (B) can choose between two measurement settings \mathbf{a} and \mathbf{a}' (\mathbf{b} and \mathbf{b}'). For each measurement setting, two outcomes, $+1$ or -1 , are possible. Realism assumes that the measurement outcomes are predetermined by some properties of the system investigated. These properties are known as hidden variables because they are not necessarily accessible to observation. The additional assumption of locality requires that the measurement outcomes on side A are independent of the measurement setting on side B, and vice versa. Thus for any given pair of particles the measurement outcomes have predetermined values $a = \pm 1$ and $a' = \pm 1$ on side A and $b = \pm 1$ and $b' = \pm 1$ on side B. These values identically satisfy the relations:

$$\begin{aligned} S_2 &\equiv a(b + b') + a'(b - b') = \pm 2 \\ S'_2 &\equiv a'(b' + b) + a(b' - b) = \pm 2. \end{aligned} \quad (1)$$

If, for example, S_2 is averaged over many trials, the absolute value must be smaller than 2, which results in the CHSH inequality [2]:

$$|E(\mathbf{a}, \mathbf{b}) + E(\mathbf{a}, \mathbf{b}') + E(\mathbf{a}', \mathbf{b}) - E(\mathbf{a}', \mathbf{b}')| \leq 2, \quad (2)$$

where the correlation, $E(\mathbf{a}, \mathbf{b})$, is the ensemble average $\langle ab \rangle$ over the product of measurement outcomes a and b for measurement settings \mathbf{a} and \mathbf{b} , respectively.

This argument can be extended to three particles [38]. We will denote the particles as well as the measurement outcomes as a , b and c , the measurement settings as \mathbf{a} , \mathbf{b} , \mathbf{c} . The outcome of each measurement can be $+1$ or -1 . If we assume local realism for each of the three particles, then for a given set of three particles the measurement outcomes a , b and c as well as their primed counterparts will have predetermined values ± 1 . Using (1) we find that the following identity must hold:

$$S_3 \equiv S_2(c + c') + S'_2(c - c') = 2(a'bc + ab'c + abc' - a'b'c') = \pm 4. \quad (3)$$

Dividing this expression by two, and averaging over many trials yields Mermin's inequality [20] for three particles:

$$|E(\mathbf{a}', \mathbf{b}, \mathbf{c}) + E(\mathbf{a}, \mathbf{b}', \mathbf{c}) + E(\mathbf{a}, \mathbf{b}, \mathbf{c}') - E(\mathbf{a}', \mathbf{b}', \mathbf{c}')| \leq 2, \quad (4)$$

where $E(\mathbf{a}, \mathbf{b}, \mathbf{c}) = \langle abc \rangle$.

Now assume that we allow arbitrary (nonlocal) correlations between just *two* of the particles, say a and b , while we still assume local realism with respect to the third particle, c . In this case we cannot factorize S_2 as we did in (1) because outcomes for particle a might nonlocally depend on the outcomes and/or measurement settings for particle b . However, we can still write

$$\begin{aligned} \tilde{S}_2 &= (ab) + (ab') + (a'b) - (a'b') \\ \tilde{S}'_2 &= (a'b') + (a'b) + (ab') - (ab), \end{aligned} \quad (5)$$

where the parentheses are meant as a reminder that these quantities should be regarded as separate and independent quantities. Each of these quantities as well as c and c' must take predetermined values ± 1 because we assume local realism with respect to the third particle. This model is strong enough to violate, and reach the algebraic maximum of Mermin's inequality (since \tilde{S}_2 can be ± 4). Thus no experimental violation of Mermin's inequality can rule out this restricted nonlocal hidden-variable model.

With this in mind let us slightly modify our argument to derive Svetlichny's inequality. Because \tilde{S}_2 and \tilde{S}'_2 are functions of the same four quantities, they are not independent. For example, whenever one of the two quantities reaches its algebraic maximum ± 4 , the other one will be 0. As a result the following identity holds:

$$\begin{aligned} \tilde{S}_2 c - \tilde{S}'_2 c' &= (ab)c + (ab)c' + (a'b)c - (a'b)c' + (a'b)c - (a'b)c' - (a'b')c - (a'b')c' \\ &= \pm 4, \pm 2, 0. \end{aligned} \quad (6)$$

Averaging over many trials yields the Svetlichny inequality:

$$\begin{aligned} \mathcal{S}_v \equiv & |E(\mathbf{a}, \mathbf{b}, \mathbf{c}) + E(\mathbf{a}, \mathbf{b}, \mathbf{c}') + E(\mathbf{a}, \mathbf{b}', \mathbf{c}) - E(\mathbf{a}, \mathbf{b}', \mathbf{c}') + \\ & E(\mathbf{a}', \mathbf{b}, \mathbf{c}) - E(\mathbf{a}', \mathbf{b}, \mathbf{c}') - E(\mathbf{a}', \mathbf{b}', \mathbf{c}) - E(\mathbf{a}', \mathbf{b}', \mathbf{c}')| \leq 4, \end{aligned} \quad (7)$$

where we refer to \mathcal{S}_v as the Svetlichny parameter. It is remarkable that, although we started out by allowing nonlocal correlations between particles a and b while c is local, one gets an expression identical to (7) if b and c are nonlocally correlated while a is local, or if a and c are nonlocally correlated while b is local. Every hidden-variable model that allows for nonlocal correlations between any two particles but not between all three can be seen as a probabilistic combination of models where the partition of the particles between nonlocal and local is made one or the other way. All of these models fulfill the Svetlichny inequality [34].

It was shown by Svetlichny that his inequality can be violated by quantum predictions, and that the maximum violation can be achieved with GHZ states. Assume we have a polarization-entangled GHZ state $|\psi\rangle = \frac{1}{\sqrt{2}}(|HHV\rangle + |VVH\rangle)$, and let our measurement settings all be in the xy -plane of the Bloch sphere, i.e. we can write the corresponding states we project on as $\frac{1}{\sqrt{2}}(|H\rangle + e^{i\phi}|V\rangle)$. For example, the measurement settings \mathbf{a} and \mathbf{a}' for

particle a correspond to projective measurements on the states $|A(\pm)\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm e^{i\phi_a}|V\rangle)$ and $|A'(\pm)\rangle = \frac{1}{\sqrt{2}}(|H\rangle \pm e^{i\phi'_a}|V\rangle)$, respectively. Here, the \pm corresponds to the state the particle is projected on if the outcome of the measurement is ± 1 . For particles b and c we choose an analogous notation. Then the quantum prediction for the left-hand side of (7) is

$$\begin{aligned} & |\cos(\phi_a + \phi_b - \phi_c) + \cos(\phi_a + \phi_b - \phi'_c) + \cos(\phi_a + \phi'_b - \phi_c) - \\ & \cos(\phi_a + \phi'_b - \phi'_c) + \cos(\phi'_a + \phi_b - \phi_c) - \cos(\phi'_a + \phi_b - \phi'_c) - \\ & \cos(\phi'_a + \phi'_b - \phi_c) - \cos(\phi'_a + \phi'_b - \phi'_c)|. \end{aligned} \quad (8)$$

With a suitable choice of angles, such as:

$$\phi_a = \frac{3\pi}{4}, \phi'_a = \frac{\pi}{4}, \phi_b = \frac{\pi}{2}, \phi'_b = 0, \phi_c = 0, \phi'_c = \frac{\pi}{2}, \quad (9)$$

this results in $\mathcal{S}_v = 4\sqrt{2} \not\leq 4$, which is the maximum violation of Svetlichny's inequality achievable with quantum mechanics [34].

Since any hidden-variable model describing a three-particle state where only two particles are nonlocally correlated has to fulfill the Svetlichny inequality, its violation explicitly rules out this type of nonlocal hidden-variable theory.

EXPERIMENT

Our experiment uses a pulsed titanium:sapphire laser (rep. rate 80MHz, 2.5 W avg. power, 790 nm center wavelength, 9 nm FWHM bandwidth). We frequency double the near-infrared beam, producing 700 mW average power near 395 nm with a FWHM bandwidth of 1.8 nm. This upconverted beam is focused on a pair of orthogonally-oriented β -Barium-Borate (BBO) nonlinear crystals [46] cut for type-I noncollinear degenerate spontaneous parametric down-conversion (SPDC) with an external half opening angle of 3° . The pump polarization is set to $|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$ such that each pump photon can produce a photon pair either in the first or the second BBO crystal. To compensate for temporal distinguishability between the pairs created in the first and the second crystal the pump passes through a 1mm α -BBO crystal, a 2mm quartz crystal, and a 0.5mm quartz crystal, all cut for maximum birefringence. To compensate the $75\mu\text{m}$ spatial walk-off between the horizontally and vertically polarized SPDC photons observed in one of the output modes, we insert a 0.75mm thick BiBO crystal cut at $\theta = 152.6^\circ$ and $\phi = 0^\circ$. For these cut angles the crystal compensates the transverse walk-off without introducing additional time walk-off. The photons are subsequently coupled into single-mode fibres. We label the two corresponding spatial output modes as 1 and 2, see figure 1(a). Fiber polarization controllers ensure that in mode 1 states in the HV basis remain unchanged while in mode 2 we flip the polarization, i.e., $H \leftrightarrow V$. With this configuration we achieve a two-photon coincidence rate of 43 kHz and single rates of about 240 kHz and 270 kHz for modes 1 and 2, respectively. The measured contrast of the pairs is 75 : 1 in the H/V basis and 61 : 1 in the $45^\circ / -45^\circ$ basis when the source is adjusted to produce $|\phi^+\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle)$ states.

Following the approach in [47] we use the double-pair emission of the SPDC source to produce 3-photon GHZ correlations in the interferometer shown in figure 1(b). A four-fold coincidence detection in the four outputs of the interferometer indicates the successful generation of the GHZ state. To lowest significant order, a four-fold coincidence can only

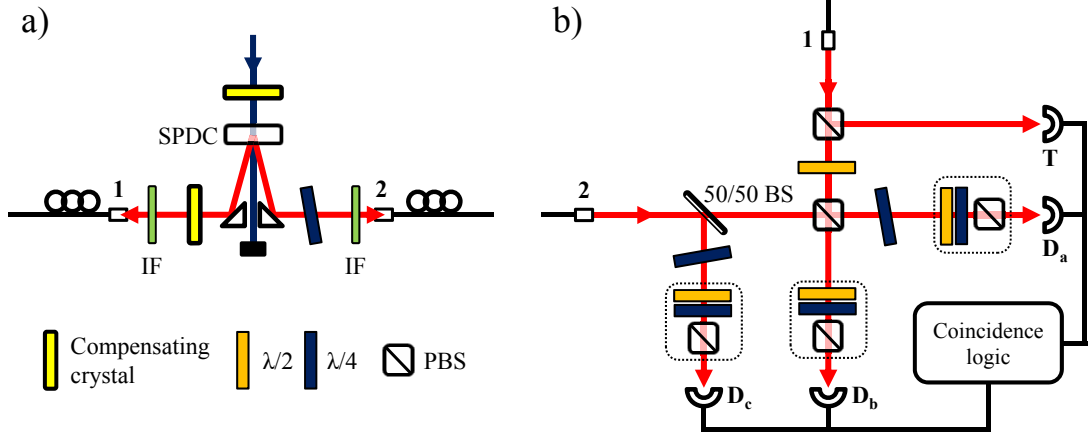


FIG. 1: Experimental setup. (a) Schematic of our type-I SPDC source. A 45° polarized, pulsed UV beam pumps a pair of orthogonally oriented BBO crystals cut for type-I phase matching. Temporal walk-off between the pairs created in the first and in the second crystal is compensated by a 1 mm thick α -BBO and two quartz crystals (one 2 mm and one 0.5 mm thick) before the SPDC crystals. Spatial walk-off, which occurred in mode 1, was compensated by a BiBO crystal. The phase between horizontal and vertical photons was adjusted by tilting a $\lambda/4$ plate in mode 2. All photons pass through 3 nm FWHM bandwidth filters around 790 nm and are coupled into single-mode fibres corresponding to the spatial modes 1 and 2. (b) The interferometer used to project on a three-photon GHZ state. Using fibre polarization controllers, the polarization in mode 2 is rotated such that we map $H \rightarrow V$ and $V \rightarrow H$, while in mode 1, H and V are preserved. Inside the interferometer the four photons from a double-pair emission can be split up into four separate spatial modes and result in a four-fold coincidence event between the detectors T , D_a , D_b , and D_c . In this case the three photons in the modes a , b , and c will be projected on the three-photon GHZ state $\frac{1}{\sqrt{2}}(|H_a H_b V_c\rangle + |V_a V_b H_c\rangle)$ given that the photons detected by D_a and D_b are indistinguishable.

occur if two photons enter the interferometer via the spatial mode 1, and their two partner photons enter it via mode 2. The two photons in input mode 1 impinge on a polarizing beam splitter (PBS). In order for a four-fold coincidence event to occur one of them must be H polarized and the other V polarized. The V photon is reflected at the PBS. Its detection by detector T serves as a trigger event. The H photon passes through the PBS in mode 1, and a $\lambda/2$ plate oriented at 22° rotates the polarization from $|H\rangle$ to $|D\rangle$. The two photons in mode 2 are split at the 50 : 50 beam splitter (BS) with probability $1/2$. Only in this case a four-fold coincidence can occur. The transmitted photon and the $|D\rangle$ polarized photon in mode 1 are overlapped on a PBS. A coincidence detection event in the two output modes of the PBS can only occur if both photons are transmitted or both are reflected. If these two possibilities are indistinguishable, Hong-Ou-Mandel interference will occur [48]. In the reflected mode of the BS we compensate for a phase shift due to birefringence in the BS by tilting a $\lambda/4$ plate.

A four-fold coincidence detection in the interferometer outputs can only occur if the trigger photon is V polarized, and if the other three photons in the modes a , b and c (see figure 1(b)) are either $|H_a H_b V_c\rangle$ or $|V_a V_b H_c\rangle$. By tilting a $\lambda/4$ plate in output mode a we

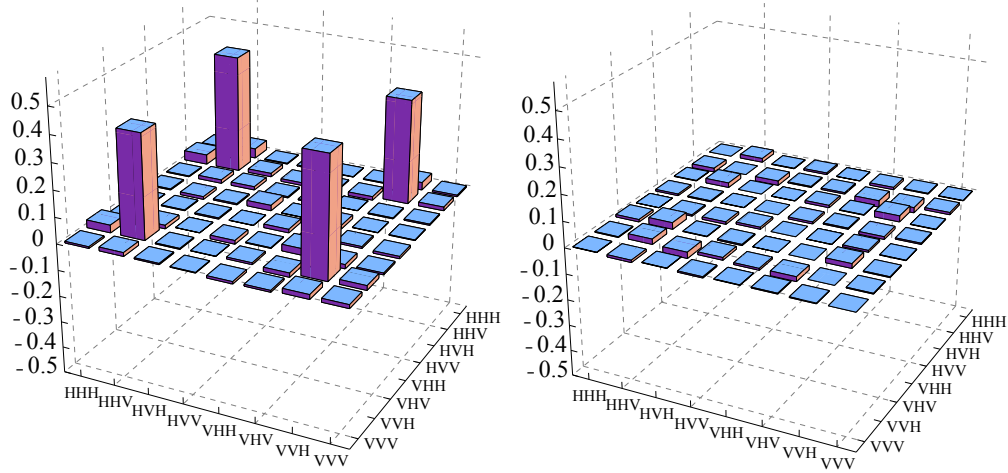


FIG. 2: Reconstructed three-photon density matrix. a) Real part and b) imaginary part of the density matrix. The state was reconstructed from a tomographically overcomplete set of 216 measurements. For each measurement the four-fold coincidence counts were integrated over 27 min, see table I. The fidelity of the reconstructed density matrix with the GHZ state $\frac{1}{\sqrt{2}}(|HHV\rangle + |VVH\rangle)$ is $(84 \pm 1)\%$.

adjust the relative phase between these contributions such that a four-fold coincidence event signals a GHZ state of the form $\frac{1}{\sqrt{2}}(|H_a H_b V_c\rangle + |V_a V_b H_c\rangle)$.

Given this state, quantum mechanics predicts a maximum violation of Svetlichny's inequality if we choose measurements of the form $|H\rangle + e^{i\phi}|V\rangle$ with the angles given in (9). Particles a , b and c are identified with photons in the interferometer output modes a , b and c , respectively. To test Svetlichny's inequality each of the photons has to be measured in two measurement bases, and for each basis there are two possible outcomes, $+1$ and -1 . For each outcome we have to set the polarization analyzer in the respective mode such that a photon detected after passing through the analyzer corresponds to that outcome.

The Svetlichny parameter, \mathcal{S}_v (see (7)), consists of 8 correlations, each of which can be constructed from 8 three-photon polarization measurements for a total of 64 measurements. Each polarization analyzer consists of a $\lambda/2$ -plate followed by a $\lambda/4$ -plate and then a PBS. The photons passing the PBSs are detected with single-mode fibre-coupled single-photon counting modules; the coincidence window is 10 ns.

In order to fully characterize the state produced by our setup we perform quantum state tomography. Because all the measurement settings for the Svetlichny inequality lie in the xy -plane of the Bloch sphere these alone are not tomographically complete. Instead of performing an additional run apart from the measurements of the Svetlichny settings, we add two additional projective measurements ($|H\rangle$ and $|V\rangle$) for each of the particles, resulting in a total of 216 three-photon polarization measurements. Our set of measurements is now actually tomographically overcomplete, which has been shown to produce better estimates of quantum states [49].

Settings for		Settings for a					
b	c	$ A(+)\rangle$	$ A(-)\rangle$	$ A'(+)\rangle$	$ A'(-)\rangle$	$ H\rangle$	$ V\rangle$
$ B(+)\rangle$	$ C(+)\rangle$	12	56	20	69	53	35
	$ C(-)\rangle$	52	19	47	18	38	32
	$ C'(+)\rangle$	12	50	43	13	31	35
	$ C'(-)\rangle$	48	16	14	56	31	23
	$ H\rangle$	34	39	32	44	4	71
	$ V\rangle$	35	26	30	29	62	8
$ B(-)\rangle$	$ C(+)\rangle$	70	16	76	12	36	35
	$ C(-)\rangle$	12	53	12	46	39	33
	$ C'(+)\rangle$	49	8	17	59	37	44
	$ C'(-)\rangle$	22	40	75	19	39	30
	$ H\rangle$	47	37	28	33	4	75
	$ V\rangle$	32	24	47	34	54	4
$ B'(+)\rangle$	$ C(+)\rangle$	19	69	57	16	40	31
	$ C(-)\rangle$	51	17	6	63	25	40
	$ C'(+)\rangle$	48	13	47	12	26	37
	$ C'(-)\rangle$	15	62	18	56	34	28
	$ H\rangle$	32	38	34	39	4	68
	$ V\rangle$	44	34	36	40	53	4
$ B'(-)\rangle$	$ C(+)\rangle$	68	18	17	62	34	36
	$ C(-)\rangle$	19	54	45	11	33	29
	$ C'(+)\rangle$	18	48	17	54	42	33
	$ C'(-)\rangle$	55	13	62	29	32	31
	$ H\rangle$	26	25	39	42	1	51
	$ V\rangle$	47	35	44	29	63	10
$ H\rangle$	$ C(+)\rangle$	42	40	39	52	77	6
	$ C(-)\rangle$	31	22	31	32	52	4
	$ C'(+)\rangle$	40	37	38	35	53	1
	$ C'(-)\rangle$	41	30	36	38	65	5
	$ H\rangle$	2	3	5	5	8	5
	$ V\rangle$	79	66	72	67	119	5
$ V\rangle$	$ C(+)\rangle$	39	46	32	43	3	72
	$ C(-)\rangle$	35	36	29	39	2	44
	$ C'(+)\rangle$	25	42	33	43	7	59
	$ C'(-)\rangle$	32	43	30	31	6	62
	$ H\rangle$	62	68	54	69	3	131
	$ V\rangle$	4	7	3	6	3	1

TABLE I: Experimentally-measured counts. Four-fold coincidences for the 216 measurements performed for quantum state tomography. A subset of 64 measured counts were used to test Svetlichny's inequality; these counts are shown in boldface type. We cycled through all of the measurements 27 times, counting for 60s for each measurement. The four-fold coincidences given are the result of integrating over all of these cycles.

RESULTS

In our setup the maximum four-fold coincidence rates of 7×10^{-2} Hz and 8×10^{-2} Hz were achieved for the correlations $|H_a H_b V_c\rangle$ and $|V_a V_b H_c\rangle$, respectively. To get statistically significant counts we integrated over 27 min per measurement. In order to reduce the negative effects of misalignment of the setup over time we realized this integration by counting for 60s for each of the 216 measurements, then repeating the full cycle of measurements 27 times. The resulting counts are given in table I.

We applied the maximum likelihood technique [50] to reconstruct the density matrix of our state. Its real and the imaginary part are shown in figure 2. The fidelity $F = \langle \psi | \rho | \psi \rangle$ of the density matrix with the GHZ state $\frac{1}{\sqrt{2}}(|HHV\rangle + |VVH\rangle)$ is 0.84 ± 0.01 . The errors of quantities derived from the reconstructed density matrix were calculated via a Monte

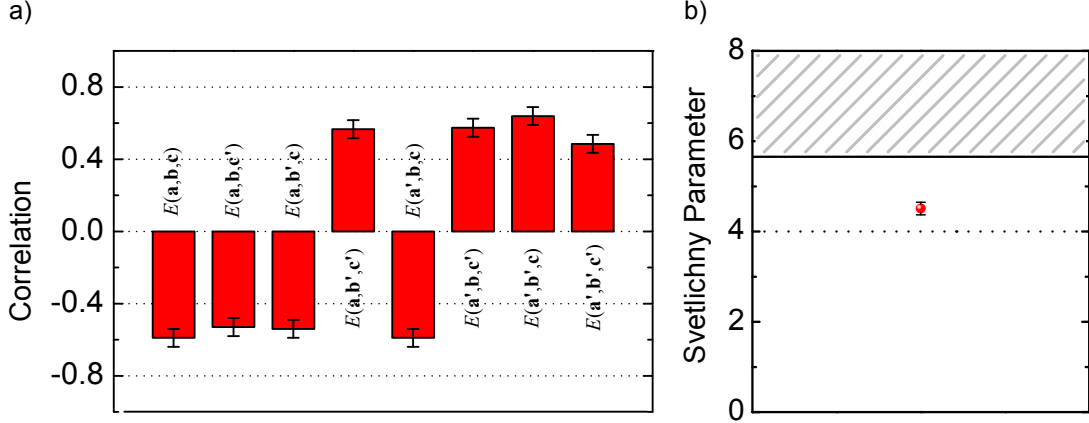


FIG. 3: Measured correlations and Svetlichny parameter. a) Measured correlations for the eight combinations of measurement settings for the three particles. Each correlation is constructed from 8 four-fold coincidence measurements integrated over 27 min. The count rates for each of these measurements are given in table I. b) These correlations yield a Svetlichny parameter of 4.51 ± 0.14 , which clearly violates the bound (dashed line) of 4 of the Svetlichny inequality. The quantum mechanical limit is $4\sqrt{2}$. Even higher values (pattern-filled region) can be reached by allowing arbitrarily strong nonlocal correlations.

Carlo simulation, where we used each of the measured counts as the mean of a Poissonian distribution. According to these distributions we generated random counts and ran the maximum likelihood algorithm. This procedure was repeated 400 times, and we report the standard deviation and mean for quantities derived from these reconstructed states.

The 64 measurements that quantum mechanics predicts to violate Svetlichny inequality are among the 216 measured. After integrating over all 27 cycles we get a Svetlichny parameter of $\mathcal{S}_v = 4.51 \pm 0.14$; the eight measured correlations are shown in figure 3. This value violates the Svetlichny inequality by 3.6 standard deviations. It is, however, in good agreement with the value, $\mathcal{S}_v^{QM} = 4.48 \pm 0.11$, predicted by quantum mechanics given the reconstructed density matrix.

CONCLUSION

We used the double-pair emission from a pulsed type-I SPDC source and projected the photons onto a GHZ state using a linear optical interferometer. We fully characterized the generated state and reconstructed the density matrix applying the maximum likelihood technique [50] using an overcomplete set of measurements. From the reconstructed density matrix, we found that our state matched the target GHZ state with a fidelity of $(84 \pm 1)\%$.

We experimentally demonstrated the violation of the original Svetlichny inequality for a three-particle GHZ state with a value of 4.51 ± 0.14 , which is greater than 4 by 3.6 standard deviations. This value is in good agreement with that predicted by quantum mechanics from our reconstructed density matrix, 4.48 ± 0.11 . By violating Svetlichny's long-standing inequality, we have shown that the correlations exhibited by three particles cannot be described by hidden-variable theories with at most two-particle nonlocality.

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